

The QuikSCAT Wind Scatterometer Mission

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Abstract— The QuikSCAT wind scatterometer, named SeaWinds, is a scanning, pencil-beam, microwave radar that was designed to measure global ocean surface winds from space. Originally planned for flight aboard the National Space Development Agency of Japan (NASDA) Advanced Earth Observing Satellite II (ADEOS-II) spacecraft, SeaWinds was expected to continue the series of Ku-band scatterometer data initiated by the NASA Scatterometer (NSCAT). Unfortunately, the failure of NSCAT's host spacecraft, ADEOS-I, prematurely ended NSCAT's mission and created a data gap. The QuikSCAT mission was rapidly developed to fill in the data gap between NSCAT on ADEOS-I and SeaWinds on ADEOS-II. A scatterometer nearly identical to SeaWinds was quickly assembled and launched on June 19, 1999 aboard the QuikSCAT spacecraft. In this paper, we describe the QuikSCAT mission, outline the key design features of the SeaWinds scatterometer, and mention some of the current and emerging science applications.

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1. INTRODUCTION

Knowledge of global ocean surface vector winds is critical for studying air-sea interaction, ocean circulation, and global climate. Also, the addition of ocean surface wind data can improve the weather prediction capabilities of global atmospheric computer models. The QuikSCAT mission was developed to aid such science by providing daily measurements of the speed and direction of winds over the ice-free oceans using a spaceborne Ku-band scatterometer called SeaWinds. Prior to the QuikSCAT mission, global ocean surface winds were measured by the NASA Scatterometer (NSCAT) aboard the ADEOS-I spacecraft. The failure of the ADEOS-I spacecraft created a gap in the global wind data set because the follow-on mission, SeaWinds on ADEOS-II, was not scheduled to be launched for several years. The QuikSCAT mission, containing a scatterometer nearly identical to SeaWinds, was rapidly developed in order to minimize the duration of the data gap

between NSCAT on ADEOS-I and SeaWinds on ADEOS-II. Since the development and launch of the QuikSCAT mission, the SeaWinds on ADEOS-II mission has been delayed by over a year, making the QuikSCAT mission even more critical. In this paper, we give an overview of the QuikSCAT mission, describe the SeaWinds scatterometer and its key features, and mention some of the current and emerging science applications.

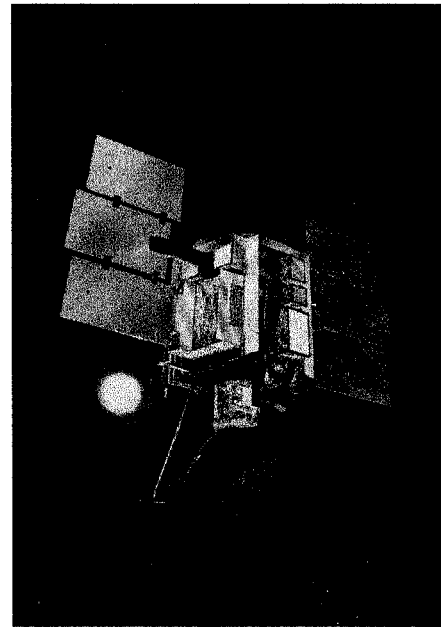


Figure 1. An artist's rendition of SeaWinds on QuikSCAT

2. THE QUIKSCAT MISSION

The QuikSCAT mission consists of a SeaWinds-class scatterometer mounted to a variation of the Ball Commercial Platform (BCP) 2000 spacecraft (see Figure 1). The scatterometer was assembled from spare flight hardware developed for the SeaWinds on ADEOS-II mission. The BCP 2000 spacecraft was obtained from Ball Aerospace via NASA's Rapid Spacecraft Acquisition (RSA) program and was the first spacecraft to be acquired using the RSA program. QuikSCAT was launched on June 19, 1999 from Vandenberg Air Force Base aboard a Titan II booster.

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QuikSCAT was placed into a 803 km altitude, sun-synchronous orbit. Although QuikSCAT's nominal mission life is two years, three years of consumables are available. The data collected by QuikSCAT are downlinked to ground stations in Alaska, Virginia, Norway, and Antarctica. The raw data are then transferred to the Jet Propulsion Laboratory (JPL) where they are processed to calibrated values of normalized radar cross section and to sea surface winds. The processed data are distributed to the scientific community via the Physical Oceanography Distributed Active Archive Center (PODAAC) at JPL. Additionally, a near-real-time QuikSCAT wind product is produced by the National Oceanographic and Atmospheric Administration (NOAA) within three hours of data collection [1].

During the first several months of the mission, the QuikSCAT system underwent an intense calibration and validation campaign. This included examining the spacecraft attitude control and knowledge errors, verifying the instrument functionality, calibrating radiometric components of the instrument, and validating the ground data processing system. The instrument was determined to be functioning properly and several calibration and algorithm corrections were made to improve the data quality [2].

3. THE SEAWINDS SCATTEROMETER

The SeaWinds scatterometer was developed by NASA/JPL to globally measure ocean surface winds in a fashion similar to its predecessors: the Seasat-A Satellite Scatterometer (SASS) and the NASA Scatterometer (NSCAT). Like all wind scatterometers, SeaWinds measures the normalized radar cross section (σ_0) of the ocean's surface from multiple azimuth angles and uses a set of σ_0 measurements at a single location to infer the wind speed and direction. The conversion of σ_0 measurements to wind vectors is called "wind retrieval" and is performed via numerical inversion of an empirical model function relating wind speed and direction to σ_0 , incidence angle, azimuth angle, and polarization.

Compact antenna design

SeaWinds is markedly different from previous scatterometers due to its compact antenna design. Previous scatterometers, including SASS, NSCAT, and the European Remote Sensing (ERS) Wind Scatterometers, have employed fixed stick antennas which produce long, narrow antenna patterns [3,4,5]. Several antennas are used to obtain measurements from the variety of azimuth angles required to invert the model function to wind vectors. Measurement resolution in the narrow-beam direction is achieved by the narrow beam width of the antenna. In the broad-beam direction, the measurement resolution is improved by using Doppler or range filtering.

Due to their large size, stick antennas can be quite difficult to accommodate on spacecraft and typically need to be stowed during launch and deployed prior to operation. Furthermore, large antennas are more likely to interfere with the field-of-view of other instruments aboard the same spacecraft. In the case of NSCAT, a special tower was constructed so that the NSCAT antennas did not block the field of view of other instruments on ADEOS-I. For accommodation reasons, the stick antenna approach was not feasible for ADEOS-II and a new, smaller antenna design was needed. The scanning pencil-beam approach was chosen because it was compact and could provide the necessary measurement geometry.

The SeaWinds pencil-beam antenna employs a 1 meter diameter parabolic dish (see Figure 2) with two offset feeds producing two antenna beams having different look (off-nadir) angles; the outer beam has a 46° look angle and the inner beam has a 40° look angle. The antenna is mechanically spun about the nadir axis so that each beam generates a circular scan on the earth (see Figure 3). The motion of the spacecraft causes each beam to trace out a helical pattern on the surface of the earth; the antenna spin rate was chosen so that the measurements from each scan overlap the measurements from the previous scan. The outer beam generates a swath which is 1800 km across and the inner beam produces a 1400 km swath. Note that measurements are made across the entire swath and that all of the measurements from a given beam have the same look angle and differ only in azimuth [6,7].



Figure 2. SeaWinds antenna assembly

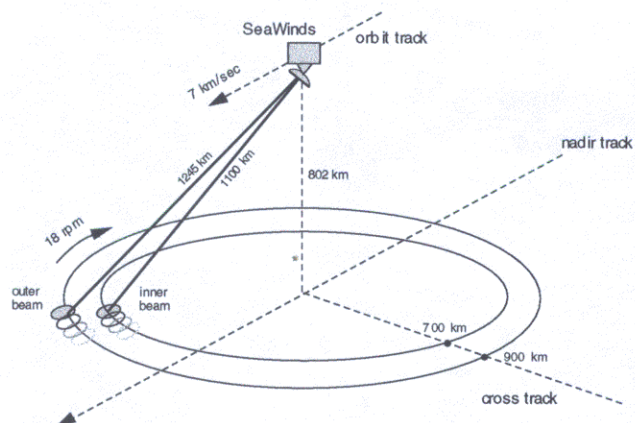


Figure 3. SeaWinds scanning geometry

SeaWinds' two beams are differently polarized; the inner beam is H polarized and the outer beam is V polarized. As previously mentioned, the geophysical model function is a function of the measurement geometry and polarization. Using both V and H polarization improves SeaWinds' ability to determine the wind direction during wind retrieval. The different polarizations are also extremely useful for land and ice applications where differences in V and H polarized σ_0 give indications of various surface attributes.

Coverage

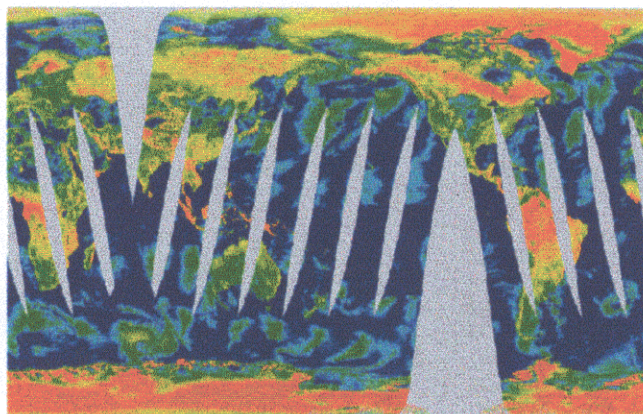
One of the benefits of the SeaWinds design is its very wide swath. Whereas previous fan-beam scatterometers did not measure σ_0 within a couple hundred kilometers of the ground track, the SeaWinds scanning pencil-beam design allows σ_0 measurements to be made across the entire 1800 km swath. This provides excellent global coverage of σ_0 . Within 12 hours, 75% of the earth is covered and within 24 hours, 92% of the earth is covered. Figure 4 shows example 12 hour and 24 coverage plots.

Near the ground track and at far swath, the geometric conditions for wind retrieval are less than ideal because the azimuth angles of the measurements are either near 0° apart or near 180° apart. This geometry provides less information for the inversion of the model function and the resulting wind solutions are less accurate.

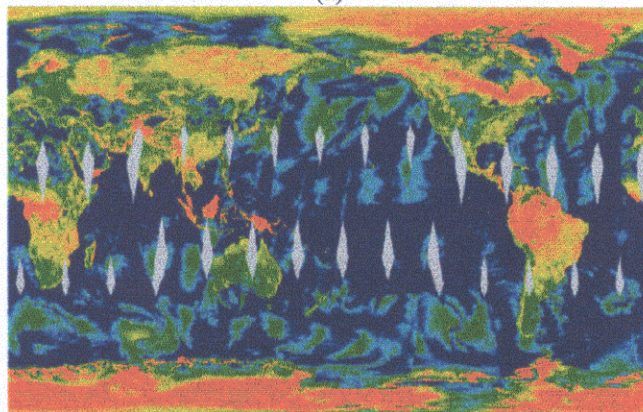
Instrument Subsystems

The SeaWinds scatterometer consists of three subsystems: the Scatterometer Electronics Subsystem (SES), the Command and Data Subsystem (CDS), and the Scatterometer Antenna Subsystem (SAS). All three subsystems and their functions are outlined below.

SES—The SES performs the radio frequency (RF) functions of SeaWinds. It contains a frequency agile transmitter, receiver, and a digital signal processor (DSP) for processing echoes into higher resolution segments called slices. Most of the echo processing is performed digitally by the DSP.



(a)



(b)

Figure 4. Earth coverage of QuikSCAT in (a) 12 hours, (b) 24 hours. Colors are used to indicate the value of σ_0 .

CDS—Essentially, the CDS is a computer which processes scatterometer commands from the spacecraft, sends timing and configuration parameters to the SES, collects measurement data from the SES, collects engineering and performance parameters from the subsystems, and transfers data to the spacecraft for downlink to the ground.

SAS—The SAS is the antenna subsystem consisting of a one meter diameter parabolic dish spun at approximately 18 revolutions per minute (rpm's). An optical encoder is used to determine the angle of the antenna at the time of the transmit event. The azimuth angle of the antenna is important both for commanding the transmit frequency and for science data processing. There are two feed horns on the antenna producing two beams with different look angles and having essentially the same azimuth angle. A summary of the key antenna and geometric parameters is given in Table 1.

Pulse Timing

For SeaWinds, the spin rate, pulse repetition frequency (PRF), and spacecraft ground velocity interact to produce the layout of measurement footprints on the earth's surface. Measurement spacing in the along-track direction is dictated by the spacecraft ground velocity and the antenna spin rate. In the along-scan direction, the spacing of measurements is

determined by the PRF and the spin rate. In order to produce sufficient overlap in both the along-scan and along-track directions, a PRF of 92.5 Hz per beam and a spin rate of 18 rpm's was chosen.

Table 1. Key SAS and Geometric Parameters

Antenna Parameter	Inner Beam	Outer Beam
Polarization	H	V
Elevation (look) angle	40°	46°
Surface incidence angle	47°	55°
Slant range	1100 km	1245 km
3-dB beam width	1.8° × 1.6°	1.7° × 1.4°
Two-way 3-dB footprint	24 × 31 km	26 × 36 km
Peak gain	38.5 dBi	39 dBi
Along-scan spacing	15 km	19 km
Along-track spacing	22 km	
Rotation rate	18 rpm	

Due to the required PRF, an interleaving pulse scheme with two pulses in flight was selected. After transmitting on a given beam, SeaWinds transmits on the other beam before receiving the echo from the first beam. Figure 5 shows the pulse timing scheme.

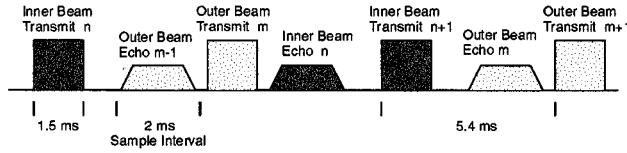


Figure 5. SeaWinds' pulse timing diagram

Range Tracking

The SES must start and stop sampling at appropriate times in order to capture all of the energy from echoes. As QuikSCAT orbits, the range to the ground changes by approximately 40 km, and the receiver must shift its sampling window accordingly. Assuring that the echo is captured in time is accomplished by a process known as range tracking. On the ground, orbital parameters are used to precalculate the appropriate round trip flight time as a function of beam, orbit position, and antenna azimuth angle. For each beam and orbit position, a sinusoid as a function of azimuth angle is fit to the round trip flight times and the coefficients are uploaded to the CDS. On-orbit, the CDS calculates the round trip flight time and commands the SES with the appropriate receiver gate delay. Figure 6 shows the commanded receiver gate delay as a function of orbit steps (1/256th of an orbit) for the inner beam.

Doppler Tracking

As the antenna scans in azimuth, the Doppler shift of the echo varies by about ± 450 kHz. This Doppler shift is due to the motion of the spacecraft relative to the earth's surface.

The SeaWinds instrument compensates for this frequency shift by using a frequency agile transmitter; the receiver frequency remains fixed, and the transmitter frequency is varied to compensate for the induced Doppler shift. In a manner very similar to range tracking, the Doppler shifts are precalculated on the ground as a function of beam, orbit position, and antenna azimuth angle, fit with a sinusoid as a function of azimuth angle, and uploaded to the CDS. Prior to each pulse, the CDS commands the SES with the appropriate transmitter frequency.

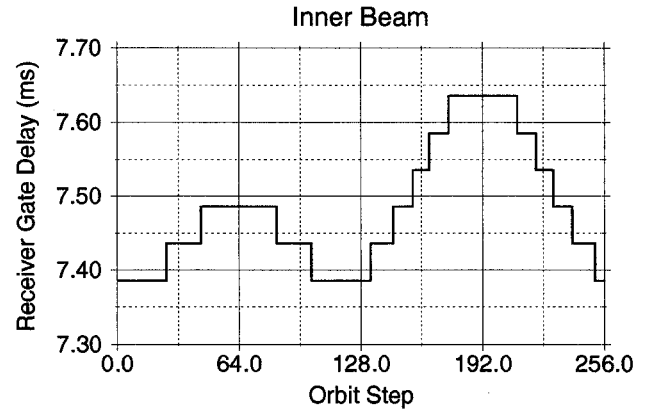


Figure 6. Receiver gate delay vs. orbit step for the inner beam

Noise Subtraction

After the transmitted energy has been scattered by the earth's surface, a portion of it returns, after several milliseconds, to the SeaWinds antenna and is routed to an analog to digital converter (A/D) for sampling. Also present, is thermal noise from both the instrument itself and from the Earth. Thus, the SeaWinds instrument actually makes a measurement of the signal plus noise. For calculating σ_0 , the backscattered signal energy needs to be isolated from the thermal noise energy. In order to isolate the echo, SeaWinds makes two simultaneous measurements. The first measurement is made using a narrow, 175 kHz, filter. The second measurement is made using a wide, 1 MHz, noise filter. We refer to the narrow filter as the "echo filter" and the wide filter as the "noise filter." Given energy measurements within these two filters, and assuming that the noise power spectral density is constant over the filter bandwidths, one can solve for the noise power spectral density and subtract the appropriate noise energy from the signal plus noise measurements to determine the echo energy.

The noise subtraction processes becomes more complicated given that we frequently have a low or even a negative signal to noise ratio (SNR), making it critical for the noise power spectral density to be estimated accurately. This means that the bandwidth and gain ratios of the echo and noise filters must be accurately calibrated. The σ_0 calculation is not very sensitive to the gain ratio, and the

gain ratio value was determined during prelaunch testing. The σ_0 calculation is sensitive to the bandwidth ratio and its value is calculated on-orbit by load measurements.

Load Measurements

Every half-scan of the antenna, backscattered echoes are ignored and both the echo filter and the noise filter are used to measure the thermal noise of a load. These measurements are incorporated into the telemetry stream and downlinked. The ground processor uses these measurements along with the prelaunch gain ratio value to estimate the echo filter to noise filter bandwidth ratio as a function of time. This ratio is used in the noise subtraction calculation.

Loop back Calibration

In order to calculate σ_0 , the combined effects (product) of the transmit power and the receiver gain must be known. The loop back calibration scheme leaks a small fraction of the transmitted signal back to the receiver through the calibration loop attenuator (see Figure 7). The losses in the loop back signal path were calibrated during prelaunch testing and the measured energy provides a means to calibrate the product of the transmit power and the receiver gain. This product is used in the calculation of σ_0 .

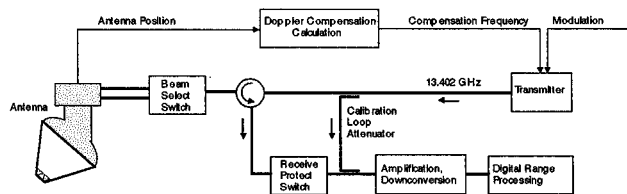


Figure 7. SeaWinds functional block diagram

σ_0 Range "Slices"

The size of SeaWinds' σ_0 measurement footprints can be as large as 26 km by 35 km. Both land and ocean science applications are enhanced by decreasing the size of the measurement footprints. To improve the resolution of σ_0 measurements in the elevation direction, range compression is employed [8].

During transmission, the transmit pulse is modulated with a 250 kHz/ms frequency modulated (FM) linear downchirp. This causes the earth to be imaged with slightly different frequencies at slightly different times. The backscattered echo is first sampled and then digitally dechirped by mixing it with a replica of the transmitted chirp. This has the effect of translating range to the earth into baseband frequency. A fast Fourier transform (FFT) is performed on the resulting data, and ranges of periodogram bins are summed to produce measurements for smaller cells on the ground. The sub-footprint measurements are called slices. Figure 8 shows a block diagram of the signal processing for slices.

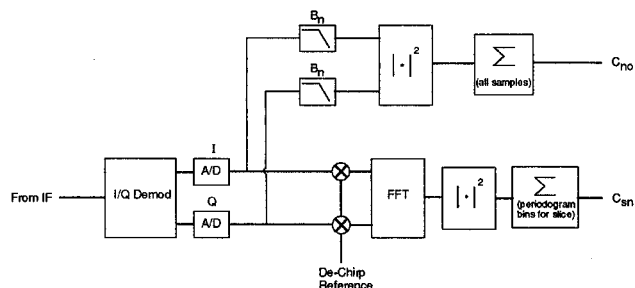


Figure 8. Block diagram of the slice signal processing.

The SeaWinds footprint is divided into twelve slices; the innermost ten slices are narrow bandwidth (8.3 kHz) and used predominantly for scientific purposes. The outermost two slices, one on each side, are larger bandwidth and are used as a frequency buffer to catch any stray energy that might leak out of the science slices and contaminate the noise filter measurement. Figure 9 shows the arrangement of slices on the earth's surface.

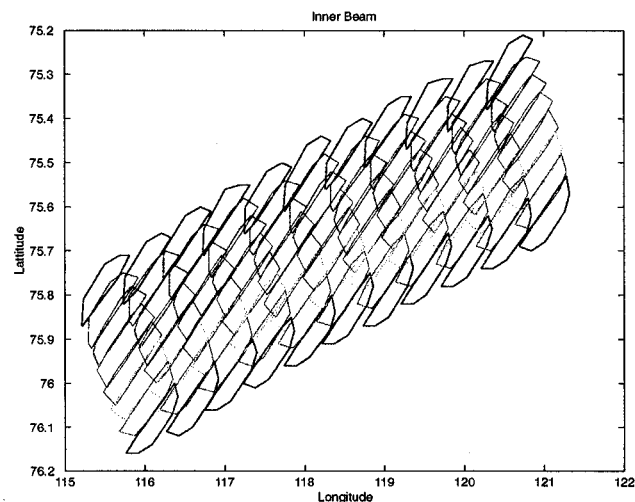


Figure 9. The center eight slices of the SeaWinds on QuikSCAT footprint. (Courtesy D. Long, Brigham Young University)

4. SCIENCE APPLICATIONS

The primary application of scatterometers is measuring global ocean surface vector winds. The SeaWinds on QuikSCAT data is processed on a 25 x 25 km grid of wind vector cells. These data can then be combined into a global wind field on a daily basis (see Figure 10).

The global coverage and high revisit rate of SeaWinds on QuikSCAT, makes its data very attractive for land and ice applications as well. Backscatter measurements from the SeaWinds scatterometer are starting to be used for global flood detection, large scale soil moisture monitoring, global snow detection, and Greenland ice melt zone detection. As an example, Figure 11 shows how SeaWinds measurements indicate the seasonal change in the soil moisture of Africa

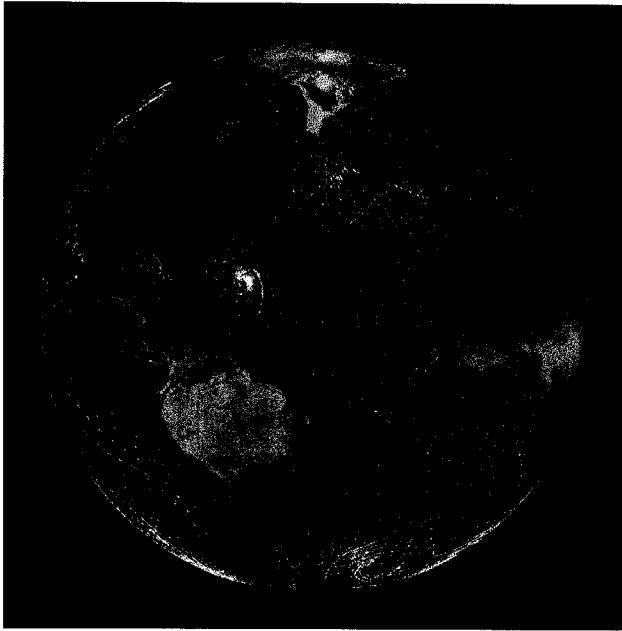


Figure 10. Snapshot of September 20, 1999. Over ocean, wind speed is indicated by color. Wind streamlines are in white. Over land and ice, the color indicates backscatter.

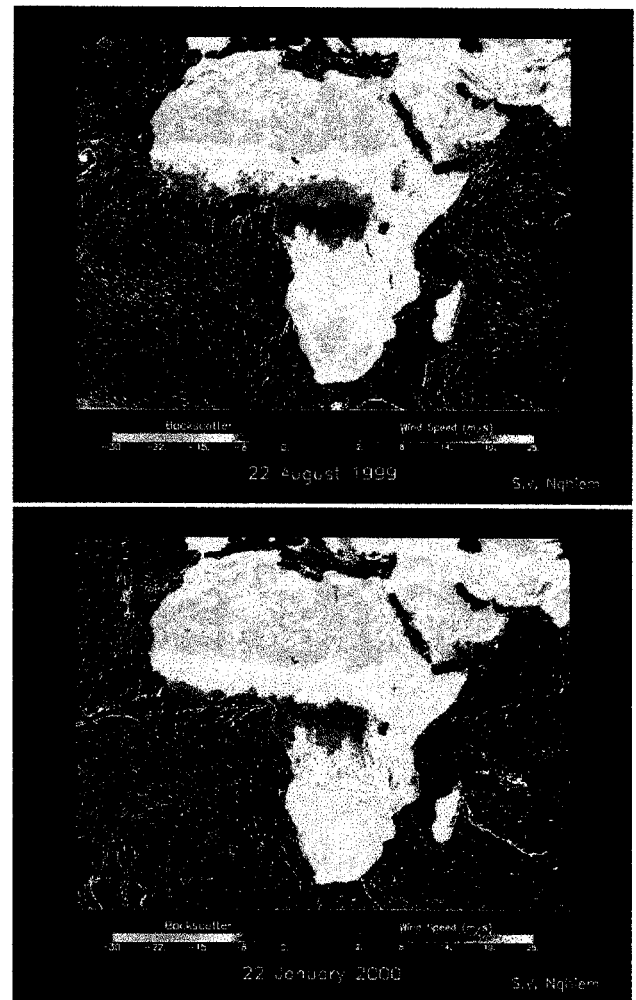


Figure 11. Seasonal variation of soil moisture pattern and wind field. (Courtesy S. Nghiem, Jet Propulsion Laboratory)

5. CONCLUSIONS

The QuikSCAT scatterometer has shown itself to be a valuable source of data, both for the estimation of global ocean surface vector winds and for studying land and ice processes. The instrument design outlined in this paper was driven by both science and accommodation constraints. Current and future science applications have been mentioned.

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